

ORIGIN OF THE CANYON DIABLO NO. 2 AND NO. 3 METEORITES

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OF the thousands of irons which have been recovered from the Arizona Meteor Crater the vast majority are coarse octahedrites. However, careful searches by Ninninger have turned up a small number of anomalous individuals designated as Canyon Diablo No. 2 and No. 3 (refs. 1 and 2). Both are medium octahedrites; they have a higher nickel content than Canyon Diablo No. 1 and often show a distorted and granulated structure.

There is no doubt that Canyon Diablo 2 and 3 are truly distinct from Canyon Diablo 1. The kamacite bands of Canyon Diablo 1 vary in width, ranging up to as much as 4-5 mm; whereas the kamacite bands in Canyon Diablo 2 average 1.4 mm in width. The nickel content of Canyon Diablo 1 is 7.11 per cent as against 8.09 per cent in Canyon Diablo 2, and the palladium concentrations are 3.98 p.p.m. and 5.30 p.p.m. respectively³. Ninninger explained these chemical and structural differences in two ways. He suggested that Canyon Diablo 2 was a swarm of small iron meteorites, captured by the main mass while the latter was in orbit round the Sun. He also offered the alternative explanation that Canyon Diablo 2 and 3 were distinct falls but thought this possibility less likely. The capture hypothesis was not widely accepted because of the obvious unlikelihood of such an event. Goldberg *et al.* pointed out that the terrain round Meteor Crater is possibly the most extensively searched area for meteoritic material. This area is about 65 km² or 1.3×10^{-7} times the Earth's surface. A fall frequency on the Earth of about 35 iron meteorites a year⁴ means that this area of 65 km² was hit on the average once in 230,000 years and twice in 460,000 years. (I have assumed that 6.7 per cent of all fallen meteorites are irons.) From other investigations⁵ it appears possible that iron meteorites can survive on the surface of the earth for a million years or longer. The hypothesis of a distinct fall is, therefore, not altogether unlikely.

The evidence for distinct origins of Canyon Diablo 1, 2 and 3 is not very convincing, however, despite the chemical and structural differences. Canyon Diablo is one of the largest iron meteorites known. Pieces of the parent mass may have been spalled off during passage through the

atmosphere and fallen near Meteor Crater. There is considerable disagreement as to the size of the projectile which produced the crater. Öpik⁶ estimates a mass of 2.6 million tons, Shoemaker⁷ gives 63,000 tons and Bjork⁸ places the mass between 30,000 and 194,000 tons, depending on impact velocity. The lowest estimate corresponds to a diameter of 19.5 m. Thus it appears almost certain that the diameter of the projectile was at least 10 m. The three Canyon Diablo varieties might have been broken out from diametrically opposed locations, and, since nothing is really known about chemical and structural variations of iron meteorites on such a scale, a third hypothesis deserves consideration in my opinion, namely the one originally rejected: that Canyon Diablo 1, 2 and 3 did all come from the same object.

An essential difference among these hypotheses is that the first two assume the anomalous Canyon Diablo to have existed in space as small individual entities, whereas the third one assumes them to have resided in a single, large parent mass. These two possibilities can be distinguished experimentally inasmuch as they should result in markedly different concentrations of cosmogenic rare gases. Signer and Nier⁹ have calculated the distribution of the cosmogenic nuclides helium-3, neon-21 and argon-38 in spherical meteoroids of different diameters, and their results are shown in Fig. 1.

This plot is based on measurements on the Grant meteorite which has a cosmic-ray exposure age of 640 ± 100 million years¹⁰. Between the break-up of its parent body, 640 m.y. ago, and its capture by the Earth, the meteorite accumulated cosmogenic nuclides which were produced by high-energy nuclear reactions between cosmic-ray particles and the atomic nuclei of the meteorite. The concentration of any stable nuclide in a sample depends, of course, on the duration of the irradiation and the location of the sample below the surface of the meteorite before the latter entered the Earth's atmosphere. While this location cannot be derived from the observed location in the recovered object, due to considerable ablation losses in the atmosphere, the ${}^3\text{He}/{}^{21}\text{Ne}$ ratio in the Signer-Nier plot is a sensitive indicator of the depth of a sample; the higher this ratio the greater was the depth.

A measurement of helium-3, neon-21 and argon-38 in any meteorite which has the same exposure age as Grant should give a point on this plot corresponding to the pre-atmospheric mass of the meteorite and the location of the sample inside the object. A difference in cosmic-ray exposure age alone would merely result in a proportionate difference in argon-38 concentration and the point would be located on a curve which can be obtained from Fig. 1 by a simple horizontal displacement of the Signer-Nier curves. Unfortunately, the pre-atmospheric mass of a

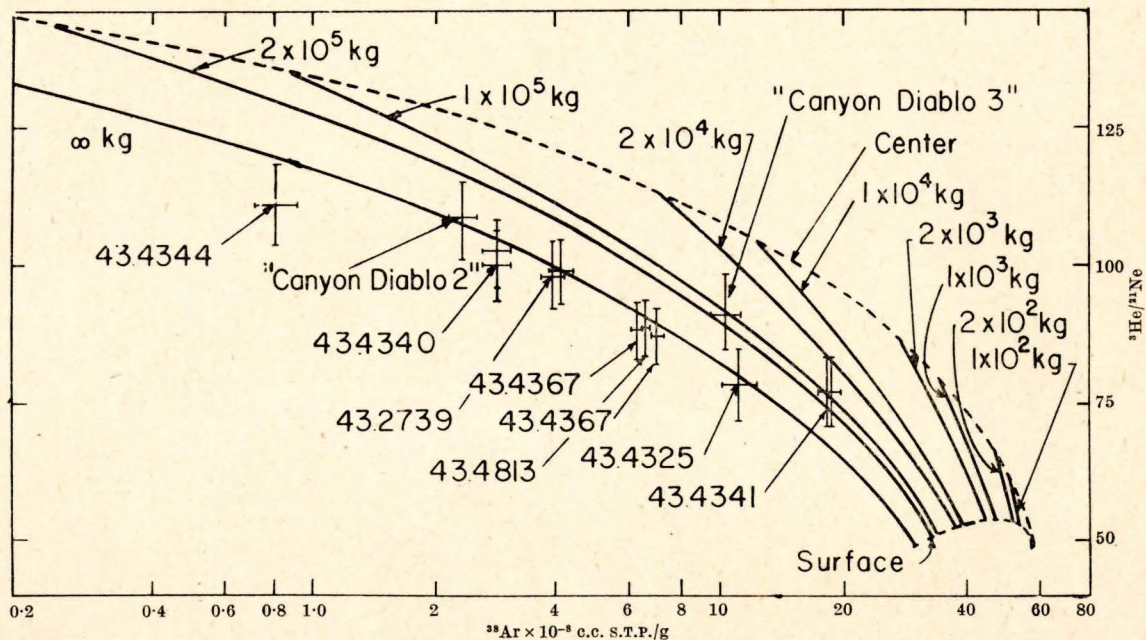


Fig. 1. $^3\text{He}/^{21}\text{Ne}$ versus ^{38}Ar for spherical meteoroids of increasing radius. The drawn curves are Signer and Nier's⁹ calculated curves. Numbered points are measurements on Canyon Diablo 1

Table 1. COSMOGENIC RARE GASES IN CANYON DIABLO NO. 2 AND NO. 3 METEORITES

Weight of sample (g)	Concentration, 10^{-8}						Ratios	
	^3He	^4He	^{21}Ne	c.c. s.t.p./g ^{36}Ar	^{38}Ar	$^3\text{He}/^{21}\text{Ne}$	$^3\text{He}/^4\text{He}$	$^3\text{He}/^{38}\text{Ar}$
1. Canyon Diablo No. 2, specimen No. 371.2								
0.3921	37.9	157	0.35	1.5	2.3	108	0.241	16.5
0.2834	34.7	151	0.33	1.4	2.3	105	0.219	15.1
0.2832	37.7	151	0.34	1.1	Lost	110	0.249	
Average	36.8	151	0.34	1.3	2.3	108	0.240	16.0
2. Canyon Diablo No. 3, specimen No. 586.1								
0.9183	180	664	1.96	6.57	10.3	92	0.271	17.5
0.6559	170	664	1.87	6.48	10.2	91	0.256	16.7
Average	175	664	1.92	6.53	10.3	92	0.264	17.0

meteorite and hence the location of a sample in the object are usually unknown, but in special cases like Canyon Diablo it is clear that points must lie close to a Signer-Nier curve of infinite mass. Note that each sphere of given mass (masses range from 100 kg to infinity, that is, $\gg 2 \times 10^5$ kg) has a maximum $^3\text{He}/^{21}\text{Ne}$ ratio which occurs at the centre of the sphere.

In Fig. 1, I have also plotted my experimental results on seven different Canyon Diablo 1 specimens. A detailed discussion of the experimental procedure will appear elsewhere¹¹. Evidently the results agree quite well with a Signer-Nier curve for a meteoroid of very large mass. The only specimen which is definitely outside the correlation is 43.4341. From the mean displacement of the Canyon Diablo 1 points to the left of the Signer-Nier curve for infinite mass, I conclude that the normal Canyon Diablo has a lower exposure age than Grant, namely 540 ± 100 million years, which is not in disagreement with a recently measured exposure age of 665 ± 65 million years by the ^{40}K - ^{41}K method¹². Shown also in Fig. 1 are results obtained on samples of Canyon Diablo 2 and 3. The results of individual measurements are given in Table 1.

The recovered mass of Canyon Diablo 2 is a few kilograms. I take this to mean that the meteorite was small, less than 500 kg if it was a 'satellite' or a distinct fall, unless most of its mass disappeared through weathering. The helium-3 content of Canyon Diablo 2, specimen 371.2, is about eight times lower than the highest helium-3 concentration measured in a Canyon Diablo iron: 301×10^{-8} c.c. s.t.p./g (43.4341). This result, taken alone, does not necessarily place Canyon Diablo 2 inside the main mass, since it is conceivable that this meteorite is a distinct fall and has a cosmic-ray exposure age of only 64 ± 12 million years. But this is unlikely. For one thing, all exposure ages of medium octahedrites measured so far are uniformly higher than 300 million years¹³. Moreover, the $^3\text{He}/^{21}\text{Ne}$ ratio of this specimen, 108 ± 7 , is much higher than what one would expect to find inside a

meteorite of a few hundred kilograms. The highest ratio observed in Grant (recovered mass 480 kg) is 82 ± 4 (ref. 10). Thus the ${}^3\text{He}/{}^{21}\text{Ne}$ ratio makes it extremely likely that specimen 371.2 was once inside a large mass: 10^4 kg or larger. Finally, the Canyon Diablo 2 point lies remarkably close to the curve defined by Canyon Diablo 1. In view of these facts, I conclude that the simplest explanation for the observed cosmogenic rare gas abundances is that Canyon Diablo 2 was once part of Canyon Diablo 1; was located approximately 50 cm below its pre-atmospheric surface; and was exposed to cosmic-ray irradiation for the same length of time as the main mass.

In the case of Canyon Diablo 3, the conclusion cannot be as definite. This iron has the third highest cosmogenic rare gas abundance of 47 Canyon Diablo individuals which I have examined. Moreover, its ${}^3\text{He}/{}^{21}\text{Ne}$ ratio does not fit well with the curve defined by Canyon Diablo 1, as can be seen from Fig. 1. The ${}^3\text{He}/{}^{21}\text{Ne}$ ratio of 92 is higher than what one would expect for this specimen: 82. Yet one detail in Fig. 1 leads me to the tentative conclusion that Canyon Diablo 3 also belonged to the main mass. Specimen 43.4341 seems to be displaced to the right of the Canyon Diablo 1 curve, yet it appears to belong to the normal variety. This could be explained in two ways. Either Canyon Diablo was broken out from its parent body 1 æon ago and suffered a second collision 540 million years ago* or specimen 43.4341 was located in a protrusion on the surface of the main mass. It can be easily shown that in the latter case the production ratios of cosmogenic nuclides are determined by the size of the protrusion, not so much by the radius of the main mass. In the present case the protrusion apparently had a mass of about 10^5 kg and a radius of 1.4 m.

Is it a coincidence that the cosmogenic rare gases in Canyon Diablo 3, specimen 586.1, can be explained with the same set of assumptions? It, too, could have come from a location in the main mass which was exposed for one æon and survived the collision 540 million years ago. Or it could likewise have come from a protrusion of about 10^5 kg which was exposed during 540 million years.

If all the varieties of the Canyon Diablo meteorite indeed come from a single parent mass, then it follows that substantial structural and compositional variations existed in the nickel-iron phase of the parent body of Canyon Diablo over distances of 10–100 m. This adds a new element of flexibility to all theories on the origin of iron meteorites.

* There is good evidence that iron meteorites suffer repeated collisions in space which produce new surfaces. Fragments from under such new surfaces have shorter exposure ages than the main mass (see: Vilesek, E., and Wänke, H., *Proc. Symp. Radioactive Dating, Athens, 1962*, 381; IAEA, Vienna, 1963). I myself have measured four Canyon Diablo 1 specimens not shown in Fig. 1, which indicate another, still shorter exposure age for this meteorite of 150–200 million years.

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- [See also p. 867 of this issue—EDITOR.]